Optimal pixel scales for NGST

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Abstract

The time required to obtain an observation of an astronomical source depends upon the characteristics of that source, the characteristics of the detector, the brightness of the background, the desired signal-to-noise ratio, and the angle subtended by a detector pixel (the pixel scale). In addition, if the observation is not of a single source but is a survey of many sources, then the field of view of the detector is also important. For a background-limited observation—expected to be the typical case for NGST—the source characteristic of importance is the solid angle of the source image. The detector characteristic of importance is the dark current. An optimal pixel scale exists that minimizes the time required to obtain the observations. That optimal scale depends upon the above variables. The Design Reference Mission (DRM) prepared by the Ad Hoc Science Working Group (ASWG) embodies the key science goals for NGST. An approximately equal amount of single-target and survey observations plus a range of target sizes comprise the DRM. Therefore, no single pixel scale is optimal for all observations. We present the functional dependence of the optimal scale upon the relevant variables. Also included are the results of parametric variations of the NGST Yardstick design which determine for each instrument module the optimal pixel scale that minimizes the time required to complete the Design Reference Mission.

Noise model

We have considered the detection of targets in the presence of Poisson noise from the target, detector dark current, Zodiacal Light, telescope thermal emission, and detector readout signals. We have developed such a model of target detection for the NGST Mission Simulator (NMS: see <http://www.ngst.stsci.edu/nms/main/>), but here we consider a scenario appropriate to NGST observations. In this simplified scenario, observations will be limited by the noise of the detector or external background, not by target noise nor readout noise. Using those assumptions, the exposure time for a single target is

$$t_1 = SNR^2 \sqrt{N_{pix,t\arg}\left(r_{dark} + s_{bkg}\Omega_{pix}\right)} \Big/ r_{t\arg}^2 , \qquad (1)$$

.

where r_{targ} and r_{dark} are the signal rates from the target and a pixel respectively, s_{bkg} is the background surface brightness, Ω_{pix} is the solid angle of a pixel, and $N_{pix,targ}$ is the effective number of pixels in the image of the target. For surveys, the exposure time will be t_{surv} = $t_1\, \rho_{targ}/\theta_{FOV}^2$, where ρ_{targ} is the surface density of desired targets. As shown below, $N_{pix,targ}$ can be expressed as

$$N_{pix,t\arg} = \sqrt{\left(\Omega_s \big/ \Omega_{pix}\right)^2 + N_{\min}^2} , \qquad (2)$$

where Ω_s is the the projected solid angle of the target image. The effective size of the target image is developed in the next section.

Image sharpness

The amount of background noise accumulated in an image is dependent on both the solid angle subtended by that image and the number of pixels in that image. The image of a point source, the PSF, subtends a finite solid angle, one which is greater than the area of the Airy disk. It can be shown that a point source is optimally detected when the image is filtered with the PSF, $\psi(x,y)$, itself. In that case, the noise is equal to that from N_{bkg} pixels given by

$$\begin{aligned} N_{bkg} &= \left[\left(\iint \psi dxdy \right)^2 \Big/ \iint \psi^2 dxdy \right] \Big/ \Omega_{pix} \\ &= \Omega_{PSF} / \Omega_{pix} \equiv 1/S \end{aligned} . \quad (3)$$

In Eq. 3, we define the image sharpenss as the inverse number of pixels and the effective solid angle subtended by the point source. For a point source, N_{bkg} is the effective number of pixels in the image. That concept can be extended to non-point sources. Generally, we approximate the solid angle subtended by the image, Ω_s, as

$$\Omega_s = \sqrt{\left(\Omega_{PSF} + \Omega_{t\arg} \right)^2} \quad (4)$$

The number of pixels in the image is considered in the next section.

Pixelization

Images of targets will not be aligned with the detector pixels in a repeatable manner, and therefore, the optimal filter defined in Eq. 3 will vary from instance to instance. However, we have determined a statistical approximation to that filter for the Airy function by carrying through a Monte Carlo simulation of that misregistration. The size of pixels relative to the features of the image also affects the weights of the optimal filter and the effective image size. Therefore, we have carried through the Monte Carlo simulation for a range of pixel sizes. The pixel size, L_{pix}, is specified in units of $\lambda/2D$, where D is the diameter of the entrance aperture. To achieve in practice a value of the normalized pixel size L_{pix}, the telescope diameter and detector pixel dimensions will be held fixed, but the reimaging camera will be designed to achieve the desired scale. The results are shown in Fig. 1a. Also shown in that figure is the fit of the function

$$N_{bkg} / L_{pix}^2 = 1.25^2 + \left(3.25/L_{pix}\right)^2 . \qquad (5)$$

For small pixels, the number varies as L_{pix}^2, but for large pixels a constant, minimum value is attained. This result is incorporated in Eq. 2. In Fig. 1b, we show how the sharpness of the NGST OTA varies as a function of wavelength. Although not used in NMS nor in the present development, the NGST sharpness is fit by

$$S = 0.045 \Big/ \left[0.047^2 + \left(2.44/(\lambda/2D)\right)^2\right]. \qquad (6)$$

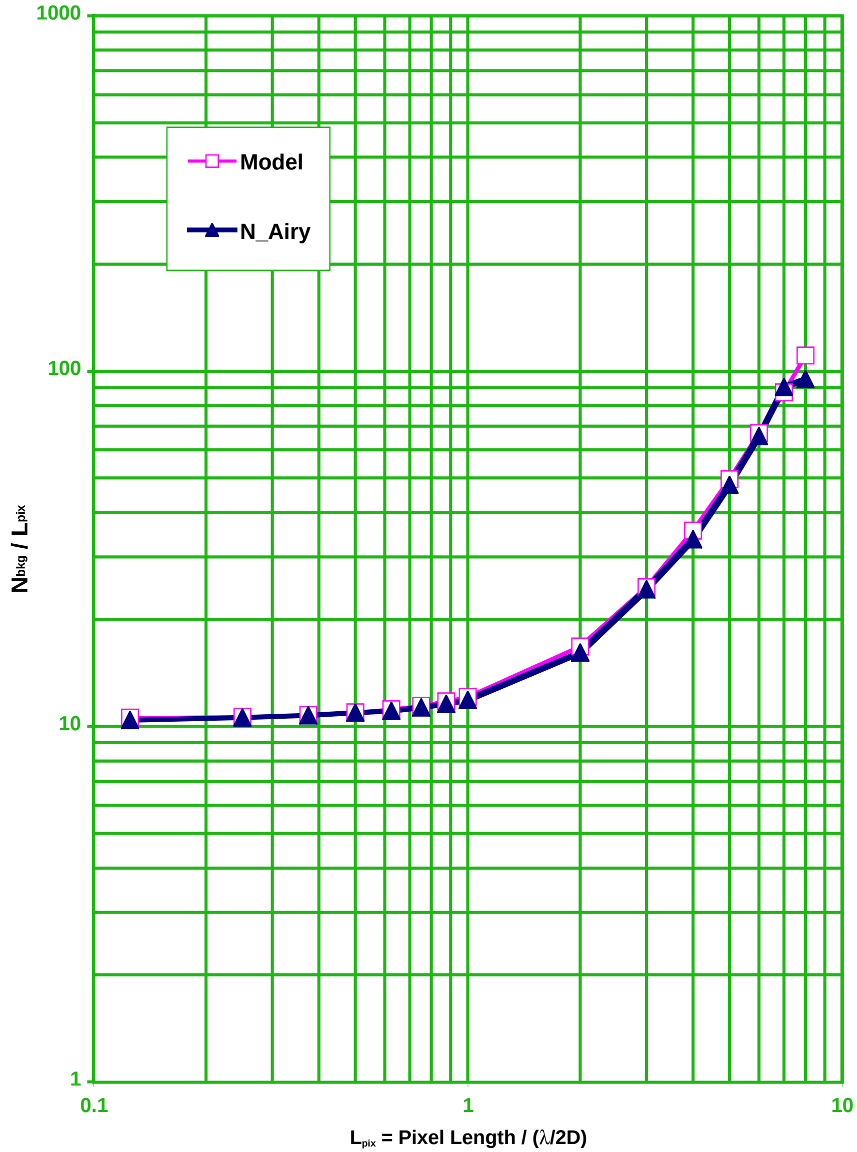

Fig. 1a: Effect of pixelation on Airy PSF sharpness as measured by the normalized, effective number of pixels in the PSF.

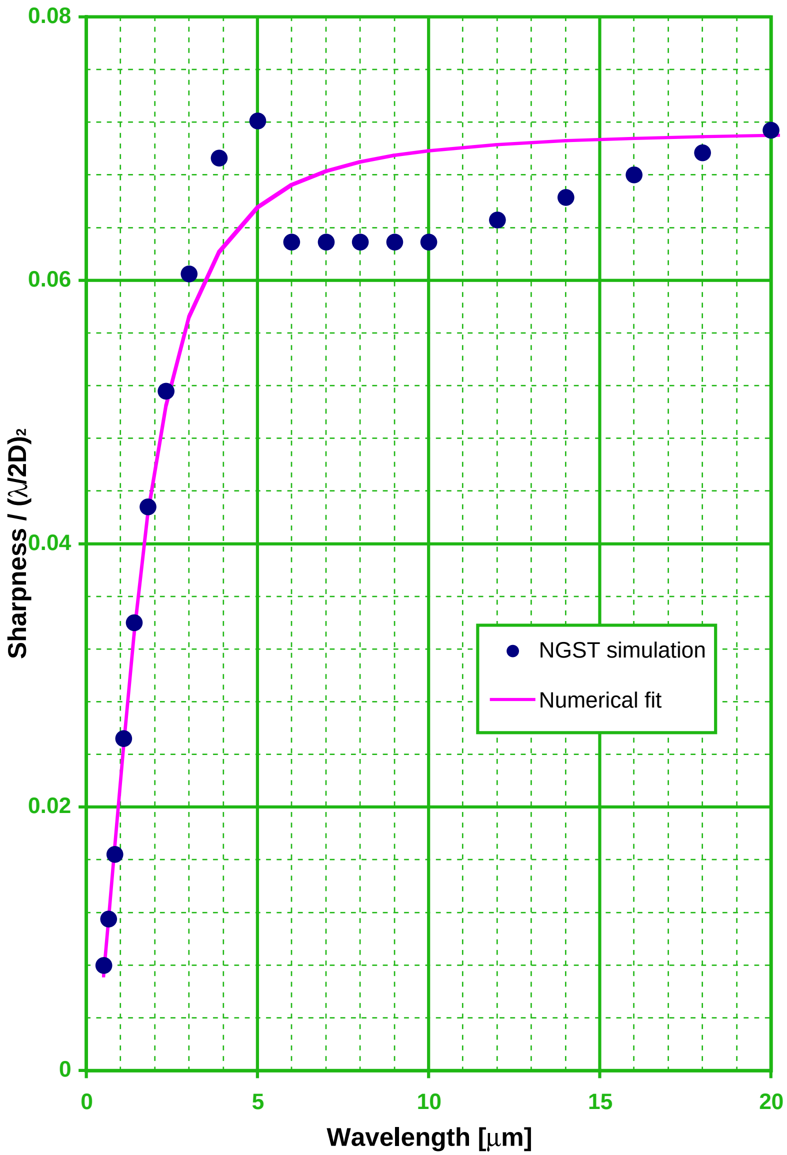

Fig 1b: Wavelength dependence of NGST PSF sharpness at λ/2D sampling. The sharpness is scaled by $(\lambda/2D)^2$.

Optimal pixel size

Combining results, the exposure time for optimal target detection is expressed in terms of the source, telescope, detector, and background characteristics as

$$t_1 = \frac{SNR^2}{r_{t\arg}^2} \sqrt{\left(\left[\frac{\Omega_s}{\Omega_{pix}} \right]^2 + N_{\min}^2 \right)^{1/2} \left(r_{dark} + s_{bkg} \Omega_{pix} \right)}. \quad (8)$$

The exposure time can be minimized by choosing the correct pixel size, namely

$$\theta_{pix} = \left(\Omega_s^2 r_{dark} \big/ N_{pix,\min} s_{bkg} \right)^{1/6}. \quad (9)$$

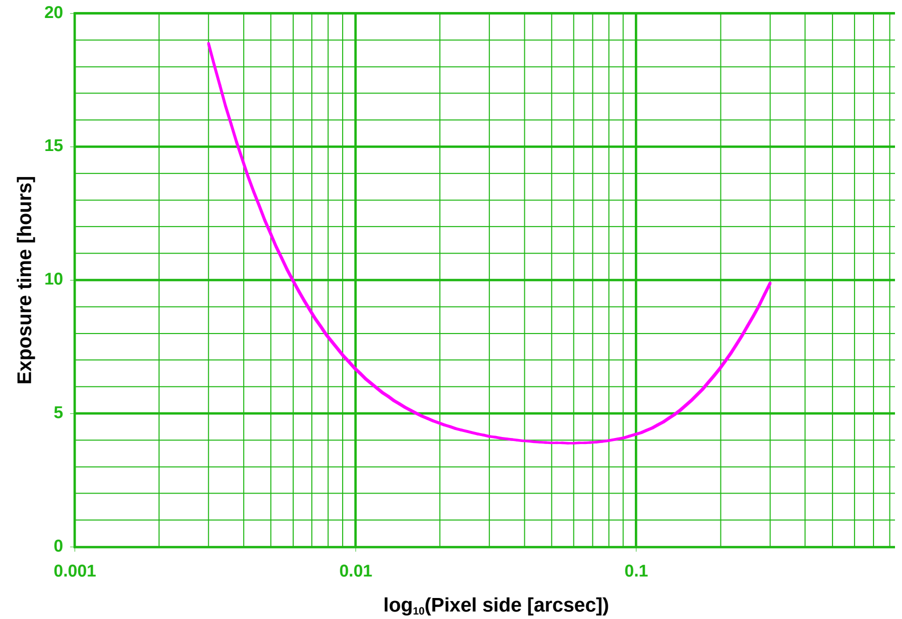

Fig. 2: Exposure time for a 2.5-μm image of a background-limited target, from Eq. 8.

To illustrate the minimization, consider the exposure time for a typical NGST NIR camera observation of a point source as a function of pixel size. From Eq. 9, the optimal pixel length is 0.06 arcsec. The evaluation of Eq. 8 is shown in Figure 2. Near the minimum, the exposure time is not greatly sensitive to the pixel size over a range of a factor of 2.

NGST Mission Simulator evaluation

Because the optimal pixel size is a function of the source size and is implicitly a function of wavelength (through the variation of the image sharpness shown in Fig. 1b), it is useful to employ a representative science program (such as the ASWG DRM) to properly weight the various contributions. The NGST Mission Simulator has been used for that purpose. In addition to the noise source described above, the NMS also includes readout noise and the effects of observing overheads. The results of varying the pixel size in the NGST Yardstick design are shown in Fig. 3. While the Mission Elapsed Time for the NIR-ACCUM, OPT-ACCUM, and MIR–SPEC can be little improved, significant gains could be achieved with an optimal pixel size for the NIR-SPEC and MIR-ACCUM instruments.

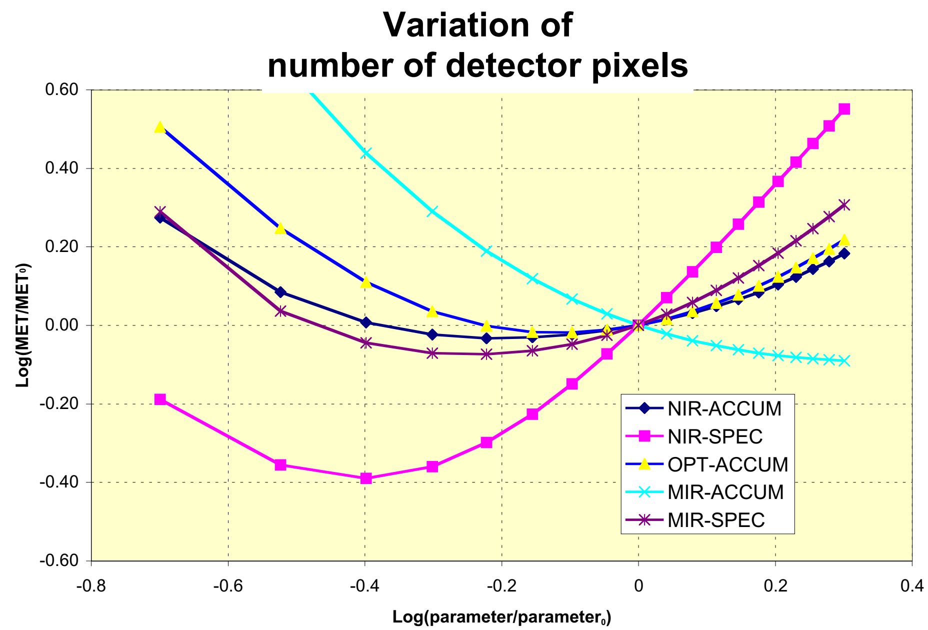

Fig. 3: Variation of Mission Elapsed Time for NGST ASWG DRM as a function of the projected angular length of a pixel side. The latter is parameterized by the number of pixels along the side of the assumed fixed FOV. The pixel size is then inversely proportional to that parameter.

Optimal pixel sizes for NGST Yardstick Design

From Fig. 3 the optimal pixel sizes can be determined. Those values are given in the following table.

Science Instrument	***Baseline pixel size [arcsec]***	***Pixel size (NMS) [arcsec]***
OPT-ACCUM	0.029	0.039
NIR-ACCUM	0.029	0.045
MIR-ACCUM	0.117	0.062
NIR-SPEC	0.044	0.110
MIR-SPEC	0.117	0.195

For all but the MIR-ACCUM instrument, the change in size of the pixel better optimizes the ratio of target signal to noise from either the external background, or the detector dark current. In this study we find that the MIR-ACCUM pixels should be smaller in order to avoid saturating the pixel well depth (assumed to be 60,000 e^-) and the associated operational overheads.